Orienteering combines vigorous-intensity exercise with navigation to improve human cognition and increase brain-derived neurotrophic factor

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Abstract

Exercise enhances aspects of human cognition, but its intensity may matter. Recent animal research suggests that vigorous exercise, which releases greater amounts of lactate, activates more brain-derived neurotrophic factor (BDNF) in the hippocampus and, thus, may be optimal

exponentially beyond the lactate threshold of ~ 4mmol/L of lactate in untrained adults [11,12]. Although lactate has historically and erroneously been considered an inert metabolic waste [13], recent evidence points to its importance as both a fuel source [14] and an activator of BDNF [15–18] with rapid effects. Mere m

Participants

exercise. The total activity amount was determined by multiplying the average length of an exercise session by the average number of active days (minutes/week).

The Navigational Strategy Questionnaire (NSQ) was used to assess participants' baseline navigational tendencies [47]. Using a 5-point Likert scale, participants rated 44 items corresponding to three different navigational strategies: allocentric spatial processing, egocentric spatial processing, and procedural processing. For each strategy, an average score was calculated.

Baseline autobiographical memory was assessed using the Survey of Autobiographical Memory (SAM; [48]. In the SAM, subjective memory is evaluated across 26 items which are answered using a 5-point Likert scale. Each item is weighted and summed to obtain an average for four memory domains including episodic, spatial, semantic, and future memory. In this study, we examined episodic and spatial memory specifically.

Lab-based baseline measurements

In the lab, before the intervention, the participant's height (centimetres), weight (intensity) + HR_{Rest}. For the moderate-intensity orienteering group, the exercise intensity range was calculated as 40-50% of HRR, and 80-85% of HRR was used for the vigorous-intensity orienteering and vigorous-intensity exercise groups.

Estimates of VO_2 peak were calculated using the *WorldFitnessLevel.org* website [50]. Participants were asked to respond to the website questions as accurately as possible and input their anthropometric and HR measurements.

Intervention measures of exercise intensity

During the intervention, HR, ratings of perceived exertion (RPE) and lactate were recorded at the middle and end of the intervention course and 10 minutes post-intervention. The highest of these values was analyzed. Heart rate was recorded using the Polar HR-10 monitor. RPE was captured using the Borg 1-20 Scale [51]. Lactate was measured from a sample of whole blood obtained from the fingertip using the Lactate Plus portable analyzer (Nova Biomedical, Waltham, MA).

Pre- and post-intervention measurements

Before the intervention, the cognitive testing was completed before obtaining a serum sample for BDNF. Following the intervention, the blood sample was collected within 10 minutes of finishing the intervention course and was followed by cognitive testing.

For BDNF, three-hour fasted samples of venous blood were obtained from a vein in the antecubital fossa. Samples were collected into BD Vacutainer SST tubes (BD, Franklin Lakes, NJ), chilled on ice, allowed to clot for a minimum of 45 minutes following sample collection and then centrifuged at 1000 x g for 15 minutes at 4°C. For all samples, 300μL of supernatant was collected to obtain serum, aliquoted into microtubes, and stored immediately at -20°C until analysis. The concentration of serum BDNF was quantified using a sandwich Biosensis Mature

BDNF Rapid^{TM} ELISA Kit (Biosensis Pty Ltd, Thebarton, Australia). Samples were diluted 100x and were run in duplicate. Using a BioTek SynergyMx spectrophotometer, absorbance was measured at 450 nm and analyzed using Gen 5 1.11 Software (BioTek Instruments Inc., Winooski, VT). Select samples whose concentration fell above the standard curve of the preliminary analysis were re-analyzed using a 125x dilution and the same protocol.

Memory was tested in two ways. First, memory was tested using Kirwan and Stark's Mnemonic Similarity Task [52–54], a modified object recognition task that places a large emphasis on high-interference memory and hippocampal function. The Mnemonic Similarity Task begins with a study phase in which participants are shown a series of images of 60 everyday objects displayed on the screen for two seconds and must classify whether the image is an 'indoor' or an 'outdoor' item. This is immediately followed by a test phase, in which participants are shown 20 'repeat' images (correct response = "old"), 20 'lure' images that are highly similar but not identical to a previous image (correct response = "similar"), and 20 completely new, 'foil,' images (correct response = "new") and asked to classify them. The Mnemonic Similarity Task has two measures which provide a valuable distinction between hippocampal-dependent high-interference memory and recognition memory. The "lure discrimination index" is a measure of high-interference memory, calculated as [*p* ("Similar" | Lure image) – *p* ("Similar" | Foil image)] × 100, and reflects one's ability to correctly classify 'lure' items as "similar". High-interference memory relies on the ability to remember specific details during encoding [55], which is dependent on the function of the hippocampus and is associated with hippocampal neurogenesis [54]. The second measure of the Mnemonic Similarity Task is general "recognition memory", defined as the ability to correctly label a 'repeat' image as "old," [*p* ("Old" | Repeat image) – *p* ("Old" | Foil image)] × 100. Recognition memory does not require

learned how to read their HR on the Polar Pacer Pro GPS watch and maintain their pace so that their HR remained in the target range. Participants in the orienteering groups (both moderate and vigorous intensity) were taught how to use the orienteering map legend, orient their map, use the map to plan a route and locate checkpoints, and retheir navigational decisions. In contrast, those in the exercise only group exercised at a vigorous intensity (80-85% of HRR) but did not engage in orienteering. Instead, a member of the research team led the participant along the most efficient route.

All participants were responsible for tracking their HR at each checkpoint and were instructed to adapt the pace or pause until their HR returned to the target zone for a maximum of one minute. At the midpoint and finish

To test for potential covariates, a one-way analysis of variance (ANOVA) was used to assess group differences in all demographic variables, weekly physical activity, spatial navigation tendencies and autobiographical memory, as well as pre-intervention differences in BDNF and cognition. To ensure that our intervention was adequate in reaching the desired exercise intensity, one-way ANOVA tests were computed for peak HR, peak RPE and peak blood lactate between groups. For blood lactate, a Kruskal-Wallis Means Ranks Test was used to confirm that the proportions of those above or below the lactate threshold of 4mmol/>f,( )] 488qQq0.00000912 0 test efficiency). Then, we performed an exploratory analysis using Spearman's correlation to evaluate the relationship between the composite cognition score with peak lactate and percent change in BDNF. Finally, we conducted a partial Spearman's correlation to determine whether the association between composite cognition score and peak lactate was diminished after controlling for the percent change in BDNF.

Secondary outcome

and memory. However, pre-intervention BDNF levels were higher for the moderate orienteering group than the vigorous orienteering or vigorous exercise groups ($p < .001$) (Table 2). Univariate ANOVA tests confirmed no other baseline differences between groups (Table 1).

Table 1. Descriptive Statistics Between Intervention Groups

Efficiency	26.12 ± 10.32	23.28 ± 6.85	24.60 ± 5.89
Pre	29.45 ± 7.88	29.42 ± 6.45	29.92 ± 4.52
Post			
Groton Maze Test Efficiency			
Pre			
Post			

Peak lactate, BDNF and cognitive function

In this exploratory analysis, the Spearman’s

Pre			
4. Groton Maze Learning Efficiency Pre	-.29	.20	.08
5. Groton Maze			

* = *p* < .05, *** = *p* <.001.

Discussion

The present study was the first to examine the effects of an acute bout of orienteering versus exercise on cognition in a sample of healthy young adults who were recreationally active but unfamiliar with orienteering. The results revealed a strong effect of exercise intensity such that the vigorous-intensity interventions in the form of either running or orienteering elicited greater increases in lactate, BDNF and memory than the moderate-intensity intervention. Additionally, vigorous orienteering improved spatial learning and memory more than vigorous running, suggesting an additional benefit of simultaneous training.

This study demonstrates a link between lactate, BDNF and cognition in humans. A novel and important finding is that the higher peak lactate induced by our vigorous exercise interventions was associated with greater percent increases in BDNF and better memory than our moderate-intensity intervention, lending support for the hypothesis that lactate mediates muscle-to-brain signalling [10,15,16,19]. Cognition was also significantly related to peak levels of lactate obtained during exercise. Interestingly, when controlling for BDNF, the relationship between cognition and lactate was no longer significant. We hypothesize that BDNF may partly underlie the effects of lactate on cognition, however, further work is needed to understand how exercise-induced lactate impacts cognition through and beyond its effects on BDNF [10,15,16,19].

On top of vigorous-intensity effects, running while navigating conferred additional benefits on our measure of spatial cognition. Spatial learning and memory were tested using the Groton Maze Learning Test, which is a close 2D analog to the 3D wayfinding of orienteering. Although all groups increased in spatial learning efficiency, the vigorous orienteering group improved the most and was the only group to improve in spatial memory after a delay. It is important to consider why. One reason relates to the specific cognitive processes tested. During the Groton Maze Learning Test, participants had to recall the maze route immediately and after a 10-minute delay, requiring skills that are highly dependent on the hippocampus, a brain region that is responsive to intervention-induced plasticity [60]. A second reason why orienteering may preferentially benefit spatial cognition relates to its overlap in cognitive processes engaged by the task. In general, cognitive training effects tend to transfer more readily to “near-transfer” tasks, i.e., tasks that closely resemble the cognitive demands of the training protocol, than “far-transfer” tasks, i.e., tasks that depend on more disparate cognitive processes [61,62]. In the case of orienteering, spatial cognition would classify as a near-transfer task and based on this framework, would be expected to benefit the most.

In contrast, the high-interference memory task would be considered a far-transfer task and, by the same logic, would be less likely to show additive effects, as was observed. Instead, high-interference memory (lure discrimination index) improved to a similar extent for both vigorous exercise and orienteering groups, suggesting that this aspect of cognition is more sensitive to the acute effects of exercise intensity than the combined effects of the exercise-cognitive training that is experienced during an acute bout of orienteering. Although the effects of vigorous exercise on high-interference memory were expected and consistent with prior work [9,56,57,63], we were surprised to observe a decrement in high-interference memory performance following moderate-intensity orienteering. This may be related to the amount of exercise-induced BDNF, which is less after moderate intensities compared to vigorous [6–8]. Indeed, those who orienteered at moderate intensity produced less BDNF than those who orienteered at a vigorous intensity, and this may have reduced their neurogenic support, rendering substrate-dependent memory benefits unobtainable.

The difference in BDNF levels between moderate and vigorous intensity orienteering may also help to explain why expert taxi drivers experience a trade-off that augments their posterior (primarily relating to spatial processing) hippocampus at the cost of their anterior (mainly involved in episodic memory) hippocampus [39]. Taxi drivers are sedentary while driving, which is in stark contrast to expert orienteers who perform their sport at a rapid running speed [29]. The lack of vigorous movement during navigation may be why we see evidence for a trade-off in expert taxi drivers but not in expert orienteers. Regardless of the mechanism, we found that engaging in vigorous-intensity exercise while that BDNF is thought to respond to energetic challenges [65], and in our sample of recreationally active younger adults, the additional challenge of running while navigating may not have been enough of an acute energetic demand. This may be especially true given the wayfinding task was short (only ~12 minutes) and across a familiar terrain. Future work should examine the potentially additive effects of orienteering versus running on BDNF using longer and less familiar routes. Additionally, there is evidence that females have lower BDNF responsivity to acute exercise [66] and lower lactate responses at the same relative exercise intensity compared to males [67]. These potential sex-based differences in lactate-induced BDNF activation may be at play with our predominately female sample (65%) and should be followed up in future work.

Despite our participants' familiarity with the campus on which the orienteering course was set, both the moderate and vigorous intensity orienteering groups travelled significantly farther and, by extension, made more errors than the most efficient route. Interestingly, the distance travelled while orienteering was associated with several of our baseline measures. Notably, those who travelled shorter distances (i.e., made fewer errors) had better spatial memory at baseline, as revealed by both self-report and task performance, which reaffirms the existence of overlapping cognitive processes engaged between navigation and spatial memory [30]. Also, those who travelled shorter distances reported greater reliance on egocentric spatial navigation. Allocentric spatial navigation was not as strongly related to course distance travelled, which was surprising given that allocentric spatial processing, like egocentric spatial processing and spatial memory, have been previously associated with expertise in the sport of orienteering [27]. The weak association between allocentric spatial processing and navigational efficiency acknowledge that navigational tendencies may differ between familiar and unfamiliar terrains [30]. For example, participants could identify campus buildings by their names and then navigate based on previously learned routes rather than utilize allocentric spatial navigation. It will be important for future work to examine the orienteering interventions across novel terrains over a variety of course difficulties.

Moreover, overreliance on GPS devices may be a factor because it minimizes active navigation and the practice of allocentric navigation in the case of “use it or lose it” [36]. GPS may be used more commonly by those with little experience in orienteering, as allocentric navigation may require more practice to be developed [30]. Unfortunately, we did not capture GPS use, but we would recommend this be done in future studies. Furthermore, prior research suggests that females may rely less on allocentric navigation than males [68], and our sample was predominantly female. Although we did not power our sample size to examine sex differences, it is recommended that future research do so. Another reason why we failed to observe a strong association between allocentric spatial processing and navigational efficiency is speculative but worth noting; this study was conducted in North America where orienteering awareness and practice is relatively limited compared to Nordic countries where orienteering is embedded into the school curricula and local cultural activities [69]. This fact should be considered when comparing studies from different countries.

Conclusion

This study demonstrates the effect of vigorous exercise on lactate, BDNF and hippocampal-dependent memory. It also reveals that orienteering may outperform exercise in improving spatial memory when done at a vigorous intensity. Together, this study establishes the

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